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Canada - Saskatchewan Renewables — Conservation Demonstration Program

Final Report

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CANADA-SASKATCHEWAN CONSERVATION AND RENEWABLE ENERGY DEMONSTRATION AGREEMENT

On March 18, 1980, the governments of Canada and Saskatchewan entered into a Conservation and Renewable Energy Demonstration Agreement. The Agreement, which terminates March 31, 1984, funds the development and demonstration of a wide range of conservation and renewable energy technologies. The program is funded on an equal cost-shared basis by Canada and Saskatchewan, and is administered by Saskatchewan.

The objectives of CREDA are:

— To develop and demonstrate promising new technologies which exploit renewable energy resources, conserve energy, or make its use more efficient;

— To create employment in new or existing industries;

— To develop broad public awareness of the potential of renewable energy and energy conservation technologies.

This report outlines the results of a project funded by the Government of Saskatchewan as represented by Saskatchewan Energy and Mines, and the Government of Canada as represented by Energy, Mines and Resources Canada, under the terms of the Renewables-Conservation Demonstration Program, and contracted with the party identified herein.

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Wind Turbines For Pumping Oil

Final Technical Report
on a Renewables-Conservation Demonstration Program Project

Conducted By

Saskatchewan Oil and Gas Corporation
Regina, Saskatchewan

And Supported By

Saskatchewan Energy and Mines
and
Energy Mines and Resources Canada

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SUMMARY

The object of this project was to assess the technical and economic feasibility of utilizing wind turbine generators to produce electrical power for operating oil well pumpjack motors.

Three Saskoil leases had wind monitoring equipment installed, which collected atmospheric data over a one year period. A review of commercially available wind turbine generators was conducted and using the atmospheric data, two different systems were designed, costed, and analyzed for techno-economic feasibility.

System I uses a wind turbine generator to supply power in an attempt to reduce utility costs at a lease presently serviced by a utility network.

System II uses a wind turbine generator to supply all the electrical power required to continuously operate a remote location lease which does not have utility power available. The wind system is compared to a remote lease which uses propane to power the pumpjack.

The report identifies the operating costs associated with each system:

System I		System II	
Utility Grid Power	$0.079/kwh	Propane powered lease	$22.94/day
Wind Generated Power	$0.210/kwh	Wind powered lease	$41.22/day

The conclusions reached were:

1. The application of wind turbine generating systems to oil well pumping operations is not economically feasible at present.

2. Both wind power systems evaluated were technically feasible to construct and operate by using existing commercial equipment.

3. The widespread use of wind power systems in the oilfield is unlikely due to factors such as unknown reliability in oil wellpumping situations, operational problems, and high operating costs.

It is recommended that future developments, such as wind power tax credits and incentives, cheaper energy storage devices, and increased utility cost, be monitored and a reassessment of wind powered oil well pumping be conducted when conditions warrant further analysis.

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The author would also like to express his appreciation to the Saskatchewan Research Council for their involvement in this project.

I. INTRODUCTION

The objective of this project is to assess the technical and economic feasibility of utilizing wind turbine generators to produce electrical power for operating oil well pumpjack motors.

Initially, three oil leases in Saskatchewan were selected for the installation of wind monitoring equipment. These three locations were monitored for windspeed, atmospheric temperature, and wind direction over a one year period. The field data collected was then analyzed and the location best suited for wind turbine performance was selected.

An analysis of two oil field operating systems was made using the wind data of the selected location. The wind turbine generating systems were selected by reviewing the specifications and performance of commercially available systems. The two operating systems studied were:

System I

This system incorporates a wind turbine generator to produce electrical power at a location presently connected to a utility network. The wind generated power would be used to operate the pumpjack motor and any surplus power produced would be fed back to the utility network reversing the power meter and lowering the electric bill. When the wind generator was not producing power, the utility network would supply power to the pumpjack motor, thus allowing uninterrupted pumping operations.

System II

This system requires the wind turbine generator to produce all the power required at a remotely located well which is not connected to a utility grid. The wind turbine would supply all the electrical power required to operate the pumpjack by incorporating a battery storage system.

The two systems were costed, and the economic feasibility was evaluated.

II. PROJECT DESCRIPTION

The objective of the project was to assess the technical and economic feasibility of utilizing wind turbines to generate on-site electrical power to run electric pumpjack motors and auxiliary oil field equipment.

The project was divided into the following six major tasks.

Task 1: Selection of Sites

Three oil well sites were selected for installation of wind monitoring equipment. Two sites were located in the southwestern region of Saskatchewan and the other in the southeastern region.

Task 2: Instrument Selection and Procurement

Wind monitoring equipment was selected and purchased. The instrumentation continuously measured and recorded wind velocity, wind direction and ambient atmospheric temperature.

Task 3: Instrument Installation

The wind monitoring equipment was installed at the three oil well sites.

Task 4: Data Collection and Analysis

Data from the three sites were collected for a one year period and analyzed to map out wind speed and direction in order to select the best of the three sites for a future wind turbine installation.

Task 5: Selection of Wind Turbine

Various types of wind turbines produced by a number of manufacturers were evaluated to select the one which best met the requirements of the job. It was essential that a specific model be chosen in order to perform a techno-economic evaluation.

Task 6: System Design, Costing and Analysis

Subsequent to the selection of the wind turbine, various back-up and energy storage systems were identified and different operating systems were studied and analyzed to select the most economically attractive system.

III. SITE SELECTION

A good wind energy system requires a realistic assessment of energy needs, and of the wind resources available. Comparing the two, an estimate of wind turbine size and type can be made.

There are two possible approaches for selecting an installation site for a wind power system: (1) visit the location where the installation of the wind machine is intended and analyze the wind resource, or (2) search for the best wind site available. It was decided to use the latter approach which promised a better opportunity for success.

General wind profile studies have been conducted for Saskatchewan, and from a study of these data it was evident that the southern third of the province has the most favourable climatology for wind power. It was decided to select three sites to monitor wind and atmospheric conditions, and to use the best of these three sites for future analysis work.

Many factors have to be considered when selecting a site for the installation of wind generators. One limiting condition of this selection was that sites had to be located near existing oil well leases owned by Saskoil. Once this constraint was accepted it was a simple matter to visit the leases and select the best sites according to the established selection criteria. Appendix A lists the considerations used in the selection of the wind monitoring sites, and the general suitability of

different terrain types for good wind conditions. Other factors considered in addition to those listed in Appendix A were:

(1) Was the lease electrified?

(2) Was there sufficient space for future installation of a turbine generating system?

(3) Was there easy access to the lease year round?

(4) Could the site be visually inspected for a commonly travelled road or would a special trip down the lease road be required?

(5) Would the installation of the wind monitoring equipment or a future wind generator interfere with the normal oil field operations or the surrounding farming operations?

Armed with the above-mentioned selection criteria, a tour of Saskoil owned and operated oil well leases was conducted in the southeast and southwest oil producing areas of Saskatchewan. Each general area was surveyed for topographical features conducive to good wind flows, and the leases closest to these good wind flow areas were identified. Three monitoring sites were eventually selected from the high potential leases identified; two in the southwest, and one in the southeast oil producing areas of Saskatchewan. All three leases were serviced with electricity, had good lease roads, and had space for placement of a wind turbine system. The following is a brief description of the three sites selected for wind monitoring.

Bone Creek 14-27-10-19 W3M

The Bone Creek site is located about thirty kilometers southwest of Gull Lake, Saskatchewan, off the Trans Canada Highway. The site is situated on a shallow ridge rising approximately sixty meters. The prevailing wind is normal to the ridge length, and has been known to blow quite strongly at this site.

Rapdan 16-5-4-20 W3M

The Rapdan site is located about 65 kilometers southwest of Shaunavon, Saskatchewan. The surrounding land could best be described as rolling prairie with the "hills" being 5 to 15 meters in height. The lease is located atop a modest hill with no major obstructions in the near vicinity.

Weyburn 10-2-7-13 W2M

The Weyburn site is located about 15 kilometers southeast of Weyburn, Saskatchewan. The surrounding topography can be correctly described as flat, bald, prairie. The lease is situated on flat land surrounded by wheat farming, and open range cattle operations.

IV. WIND MONITORING INSTRUMENTATION

Once the three sites had been selected, it was necessary to determine an accurate assessment of the wind energy resource in each area. As the basic requirements for conducting a site survey are a record of wind speed, wind direction, and ambient air temperature, it was necessary to obtain instrumentation that would measure these factors and permanently record them without constant human supervision.

For the instrumentation the Climatronics Electronic Weather Station (distributed in Canada by M.I.C. Company, 216 Duncan road, Thornhill, Ontario L3T 3N8, [416] 889-6653) was chosen. The Climatronics system uses an analogue stripchart recorder which registers a complete month of data before a chart change is required. The recording system is contained in a weatherproof fiberglass enclosure which protects the equipment. The sensors included with the system are a rotating cup anemometer using a solid state light source and photochopper to sense wind speed. A vane-type wind direction sensor, using a precision poteniometer with 540° output, and a temperature sensor, utilizing a precision thermistor, were also included. Table 1 provides a brief description of the weather station and the general specifications.

The wind instruments (sensors) were mounted atop a standard television antenna mast at a height of 9m (30 ft.) from ground level. The

mast was mounted on a concrete footing, and guy wires prevented movement at the top.

The recording units at two locations were electrically powered from the lease facilities while one monitoring system used batteries because of hook-up problems. The recording units were also placed in a foam insulated box which afforded additional weather protection and easy access, especially during the winter season.

Total cost for a single Climatronics Electronic Weather Station, complete with wind speed, wind direction and temperature sensors, and a mounting mast, was approximately $5,400.00.

V. WIND DATA COLLECTION AND ANALYSIS

The three wind monitoring stations collected data for a one year period from December 1981 to November 1982 inclusive. As noted previously, wind speed, wind direction, and atmospheric temperature were recorded on a continuous basis during the entire period.

The information from the wind monitoring equipment was recorded on stripcharts, with each chart containing one month's data. An example of a typical stripchart is shown in Figure No. 1. The stripcharts were replaced monthly by Saskoil field personnel who also visually inspected the monitoring stations as part of their daily routine.

Windspeed is the most important factor in assessing the amount of wind energy available at a particular site. The stripcharts were sent in from the field and the data was manually extracted. The average windspeed over each one hour period and the instantaneous windspeed were read on the hour and tabulated for each day. A sample of a daily record sheet is shown in Table No. 2. Hourly temperature and wind direction were also read and tabulated on the daily record sheets. Peak wind gust velocity, or the highest recorded windspeed during the day, was also tabulated along with the time at which it occurred.

When the tabulation task was completed, a total of over 100,000 data entries had been made for the three monitoring sites and over 1,000 daily record sheets prepared. Needless to say, data presented in this manner are not very conducive to the detailed analysis required to determine the wind energy resources for each location. It was necessary to arrange the information obtained at the monitoring sites into a useful form; the easiest method of accomplishing this was through the use of a computer. The computer arranged the thousands of recorded events into categories saving hours of hand calculations. A description of the major parameters anlayzed follows.

Windspeed

The most useful representation of windspeed is perhaps the annual windspeed distribution curve, which reveals that a certain windspeed can be expected for a certain percentage of the time. It does not disclose when to expect that windspeed or how long it will persist. The annual windspeed distribution curves for the three monitoring sites are shown as Figures 2, 3 and 4. Tables 3, 4 and 5 contain the data entries used to prepare the windspeed distribution curves as arranged by the computer.

Also included with the windspeed distribution curves in Figures 2, 3 and 4 is a curve labelled Rayleigh Distribution. The Rayleigh Distribution is a statistical approximation of the windspeed distribution

curve and requires only the knowledge of mean windspeed at a site to generate the curve. The Rayleigh Distribution was added to the graphs for comparison purposes to determine the correlation with the observed data. At windspeeds below 4.5 meter/second or 16 km/hr, it appears the Rayleigh Distribution correlates poorly with the observed data. The Rayleigh Distribution takes the following form:

$$H = 8{,}760 \times \frac{\pi}{2} \times \frac{v}{\bar{v}^2} \times e^{-\kappa}$$

where: H = number of hours per year at windspeed v

v = windspeed

$\bar{v}$ = mean windspeed

π = 3.1416

e = base of the natural logarithm = 2.7183

$$\kappa = \frac{\pi}{4} \left(\frac{v}{\bar{v}}\right)^2$$

This equation gives the total number of hours per year the wind can be expected to blow at a windspeed v when the mean windspeed is $\bar{v}$ at that site.

The mean or average windspeeds for the three sites are as follows:

Bone Creek	18.0 km/hr or 5.0 m/s
Rapdan	10.8 km/hr or 3.0 m/s
Weyburn	11.1 km/hr or 3.1 m/s

The Bone Creek site records the highest mean windspeed by an appreciable margin, and was selected as the best candidate for additional study.

Wind Energy and Wind Power

The wind energy or kinetic energy available in a unit volume of air depends only upon the air density ρ and the instantaneous windspeed v. The familiar formula for kinetic energy per unit volume is given below:

$$\frac{\text{kinetic energy}}{\text{unit volume}} = \frac{1}{2} \times \rho \times v^2$$

To find the available energy in a moving stream of air multiply the above equation by the volume of air:

$$\text{Volume} = v \times A \times t$$

where: v = windspeed

A = cross sectional area

(swept surface area of turbine rotor)

t = time

Combining the two equations gives the available energy contained in a defined stream of air:

$$\text{Available Energy} = \frac{1}{2} \times \rho \times v^3 \times A \times t$$

Power is energy per unit time. Therefore, if you divide available energy by time, the result is available power which is given by the equation:

$$\text{Available Power} = \frac{1}{2} \times e \times v^3 \times A$$

Unfortunately not all of the available power described by the above equation can be converted to useful work. Only 59.3% of the available power can be removed from a moving stream of air. Therefore, the equation to describe the maximum power that can be obtained from a moving stream of air is:

$$\text{Maximum Power} = \frac{0.593}{2} \times \rho \times v^3 \times A$$

The factor 0.593 is known as the Betz coefficient, named after the man who first derived it.

The units used in the above equations are:

Maximum Power - watts

Available Power - watts

Air Density ρ - grams/litre or kg/m^3

Windspeed v - metres/second (m/s)

Area A - square metres (m^2)

Air density ρ changes with temperature, barometric pressure and the water content of the air (humidity). To obtain an air density at any condition, air density reference tables can be used. The value for air density at 760 mmHg barometric pressure and 20°C is 1.2047 g/l for dry air.

Using the available power equation, the power available at the Bone Creek site was calculated, and is shown as Figure 5. This graph was prepared assuming an area A of 1.0 m^2. For each windspeed velocity a power value was determined which was then multiplied by the number of hours in a year that the corresponding windspeed occurred. This resulted in a value with the units watt-hour/m^2-year, or the number of watt-hour for every square metre over a one year period. This value was then divided by 1000 to obtain units of kw-hr/m^2-year.

The majority of the available wind power occurs with windspeeds over 8.0 m/s. It is evident from the power distribution graph that even though the mean windspeed is 5.0 m/s the higher windspeeds account for the majority of the power available at the site.

The total available wind power during one year can be determined by adding all the power values for each velocity in the power distribution graph. This is equivalent to integrating the power distribution curve. The Bone Creek site, therefore, has a total available power value of 3,100 kw-hr/m^2 for a one year period.

Wind Direction

Local winds are generally influenced by pressure and temperature differences across a few miles of land. These local atmospheric influences combined with those of hills, trees, and other topographical features, can cause wind to shift directions frequently. It is important to recognize from which direction the majority of the wind blows at a particular site. Placement of a wind turbine on a site should be determined so the prevailing winds approach the turbine unhampered by obstructions. The easiest method to visually display windspeed frequency by direction is through the use of a "wind rose". The wind rose for the Bone Creek site is shown in Figure 6, and Table 6 shows the frequency distribution in tabular form.

The wind direction data as received from the field were divided into eight specific directions and the frequency of each direction was calculated by the computer. The wind rose demonstrates that over 60% of the winds prevail from the south, northwest, and westerly directions with the other five directions accounting for less than 40% of the wind.

An analysis of windspeed by compass direction is presented in Table 7. This table indicates that although 20% of the wind comes from the southerly direction the associated windspeeds are generally lower than 20 km/h or 5.6 m/s.

Thus, little power can be extracted from these winds. At windspeeds above 20 km/h the predominant wind direction is west and northwest. These are the winds with the majority of available wind power. The west to northwest direction of this site would be referred to as the "fetch area" or the direction from which the most powerful winds prevail.

Atmospheric Temperature

Atmospheric temperature, although recorded on the daily reports, was not included in the computer analysis. As interesting as temperature readings can be, the only real application of this data is to determine accurate air densities, and to identify adverse conditions such as extremely cold days which are beyond the design operating temperature of the wind turbine unit.

The windspeed distribution by temperature was not investigated as this is mainly used where a wind turbine is supplying energy for heating purposes.

V. FIELD OPERATIONS - TWO SYSTEMS

Virtually all produced crude oil in Saskatchewan is mechanically pumped from underground reservoirs to the surface. This is accomplished by placing a piston pump on the end of a tubing string, thus locating the pump below the oil level in the wellbore. The bottomhole piston pump is actuated by a long steel rod, referred to as a sucker rod, which is placed inside the tubing string and is attached at one end to the piston pump and at the other end to the pumpjack or the surface. The pumpjack strokes the sucker rod up and down moving the piston in the bottomhole pump which displaces oil through the annular area between the tubing and sucker rod and eventually to the surface.

The pumpjack, or the familiar "horsehead" surface pumping unit, is generally powered by one of two prime mover types; either an electric motor or an internal combustion engine. Usually the electric motor drive is chosen if possible because of its reliability, ease of operation and low operating cost. Unfortunately, in order to use an electric motor the producing well must be near a power grid. When electrical power is not available, an internal combustion engine is used to power the pumpjack. This internal combustion engine is often fuelled by natural gas from the oil well. In certain instances an insufficient amount of natural gas is produced requiring the use of propane to fuel the engine. The use of propane is very costly compared to electricity, or to natural gas which is essentially free.

We investigated the use of wind turbine generating systems as they applied to two operating situations in the oil field. The two systems studied were:

System I

A wind turbine generating unit used to supply a substantial portion of the electrical power requirements of a lease that is electrified. The power generated by the wind turbine would be used to drive the pumpjack motor and any surplus power produced would be "fed back" to the utility grid reversing the power meter and lowering electrical costs. In situations where the wind turbine was not producing sufficient power, the utility grid would supply the power deficit needed to maintain pumping operations.

This system would be very reliable, as two power sources would be available to operate the pumpjack. It is very important that pumping operations not be interrupted because pump downtime is essentially lost production and lost revenue which can quickly add up if the well is a good producer.

System II

A wind turbine generator used at a remote location that normally would be powered by propane fuel. The wind turbine would supply all of

the electrical power required to drive the pumpjack. A battery storage system would be employed to ensure operation during periods of low windspeed.

System II is necessarily more complicated and more expensive than System I. It was, however, compared to the most expensive operating case; the use of propane fuel to power a pumpjack.

An analysis of these two systems should indicate whether the use of wind turbine generators is practical and an economic possibility in the oil field.

VII. EVALUATON OF ENERGY NEEDS

Wind system design is a process of balancing energy needs against energy availability. The energy requirements of the two previously described systems must be based as closely as possible on actual operating conditions. Since the Bone Creek lease has been selected as the most favourable site for wind energy production, it was decided to use actual operating data from this lease for the analysis of the two systems to be studied.

System I used actual power consumption figures for the Bone Creek well derived from Saskatchewan Power Corporation billings. System II analysis also used the Bone Creek wind data and power consumption figures, but assumed the well was at a remote location not connected to a utility grid.

The Bone Creek pumpjack is driven by an alternating current, squirrel-cage type, 1200 rpm synchronous speed, 440 volt, 3-phase, 60-cycle, 15 hp, induction motor. Continuous power demand is 3750 watts or approximately 5 hp. Daily power consumption is 90 kwh and when the unit is operated continuously for a year, total power consumption is 32,850 kwh.

Power requirements for System I are clearly identified and easily met by the utility grid, and the wind turbine would simply supply power when available to reduce total power consumption.

System II power requirements were more difficult to determine. The system must supply continuous power totally independent of any utility network. It must have a storage capacity large enough to provide not only continuous power over periods when there is insufficient wind but also have enough instantaneous reserve to supply power for motor start-up. A review of wind data for the Bone Creek site indicated there were two seven day periods during the year when the wind was not strong enough to produce any power. If continuous operation is required, the battery storage must therefore contain enough reserve for at least seven days of operation. Also important is the the peak current demand by the electric motor for starting operations. The battery system must be able to deliver this short surge of power.

VIII. WIND TURBINE GENERATOR SELECTION

The choice of the correct wind turbine generator for each of the two systems depends on many operational and design factors. Initiating the selection process required an investigation of the wind turbine generating units commercially available. Various sources were reviewed and a list of manufacturers was compiled (Appendix B). Also included in Appendix B is a copy of "Commercially Available Small Wind Systems and Equipment", March 31, 1981, Rockwell International and a copy of "33 Windmills You Can Buy Now!", July 1982, Popular Science. The information was reviewed and sixteen possible wind turbine systems identified. The sixteen manufacturers were contacted and requested to submit specifications and cost information for their systems. Complete details for these systems are contained in Appendix C.

The various factors considered for the wind turbine selection for each system are described below.

System I

As previously indicated, this system was designed to investigate the feasibility of using a wind turbine generator to supply supplemental power to an oil well pumping installation which is being serviced by power from a utility network. The grid will supply power when the wind generated power production cannot match demand. If wind generated power

exceeds demand, the surplus power will be backfed into the utility grid, reversing the power meter and lowering indicated power consumption and utility costs. This system would be very reliable because there are two alternate sources of power.

The key question is whether the wind generator can produce electrical power at a lower cost than that supplied by the utility network.

The sixteen wind turbine systems identified as possible candidates for the study were reviewed and analyzed for cost per kilowatt produced. The goal was to select a 'wind generator' that over a one year period would produce a reasonable amount of the power required by the pumpjack, thereby decreasing operating costs. Oversizing the wind generator to produce more power than required was avoided because it was unlikely the utility company would pay for any excess power produced.

The Tumac Model 680 wind turbine generator was selected as the best candidate for System I. The Tumac produces a maximum of 9.2 kw at 16 m/s, and is rated at 8 kw at a continuous windspeed of 13 m/s. The turbine is a free standing vertical axis Darreius type mounted on a single mast that requires no guy cables. The power output curve (Figure 7) for the Tumac fits well with the windpower distribution curve of the Bone Creek site indicating a good match. The generator section is an induction type that can be connected directly to a utility grid without any special

interfacing devices. Complete specifications for the Tumac wind generator are contained in Appendix C.

An analysis of the actual power the Tumac wind generator would produce at the Bone Creek site was conducted. This was calculated by multiplying the duration time of each windspeed from the Bone Creek site with the specific power produced by the Tumac at that windspeed, and then adding all the values at each windspeed to arrive at a total. This power distribution curve is shown as Figure No. 8 and detailed values are included in Table No. 8. The total yearly power the Tumac would generate at Bone Creek is 16,436 kwh. If the Bone Creek pumpjack was operated continuously over a year, it would require 32,850 kwh, therefore, the Tumac is capable of supplying only 50% of the maximum power requirements. In actual practice the pumpjack operates an average of about 85% of the time over a year. This is due to maintenance shutdowns, monthly production limits, and other operational problems that are always encountered. The Tumac can supply approximately 60% of the total system power requirements.

Installation at the site would be a simple procedure which would require that a pile be installed for the mounting mast and that direct electrical connection be made to the utility grid.

System II

As discussed earlier, System II was designed to investigate the

feasibility of using a wind turbine generator to supply the complete power requirements of an oil well pumping installation.

The system would require the use of power storage to maintain continuous operation.

Wind turbine generators have a minimum "startup" windspeed below which no power is produced. This minimum windspeed ranges from 3.5 to 7 m/s depending on the specific wind turbine. If we assume a windspeed value of 5.0 m/s before any appreciable power is produced, we can observe from the Bone Creek wind distribution curve (Figure No. 2) that windspeeds greater than 5 m/s occur only 50% of the time. In other words, a wind turbine generator, no matter what size, can only supply power for half the time without a reserve power system.

The most commonly used power storage device for wind-electric systems is the lead-acid battery. When the wind generator produced power, the power would primarily be used to operate the pumpjack motor, and any surplus power produced would be shunted over to charge the batteries. In situations where the windspeed was below the minimum start-up speed, and no power was produced, the batteries would provide full operating power. It would also be possible for the wind generator to produce power at levels less than required by the pumpjack motor, in which case the electrical load would be shared between the wind generator and the battery storage system.

The battery storage system must have sufficient reserves to sustain

pumpjack operation over the longest period of zero power output from the wind generator. Analysis of the wind data showed that seven consecutive days was the longest period when windspeeds did not exceed 3.5 m/s. It was decided therefore, to use seven days of reserve power at constant operating conditions as the design capacity of the battery reserve system. The constant power demand of the Bone Creek pumpjack motor is 3.75 kw which translates to 630 kwh over a seven day period. A heavy duty 12 volt automobile battery commonly has a rating of 200 amp-hr which when multiplied by 12 volts equals 2400 watt-hour or 2.4 kwh. The design capacity of the battery reserve system is 630 kwh and therefore requires the equivalent of about 263 automobile batteries. The batteries selected for this system are lead acid batteries as are automobile batteries but are large stationary batteries designed for "deep cycling" or constant charge-discharge operation.

As determined previously, to operate the pumpjack motor continuously, the total yearly power consumption would be 32,850 kwh. This would require a wind turbine generator which produces at least this much power with the wind regime at the Bone Creek site. In actual fact, more power than 32,850 kwh will have to be produced to compensate for electrical system inefficiences. Wind turbine generators producing power at this level are necessarily alternating current machines, and unfortunately batteries are direct current devices. In order to charge the batteries, it is necessary to convert the alternating current from the wind generator to DC current by the use of a full wave rectifier unit. This conversion is not 100% efficient. Also, some loss of DC power

occurs when it is delivered to the batteries as the charging process is not 100% efficient. The overall efficiency from produced AC current to the power actually stored in the batteries is approximately 70%, therefore, for every 100 watts produced by the wind generator only 70 watts are finally stored in the batteries.

The batteries must supply power to the pumpjack motor when the wind turbine is not producing power. As the pumpjack motor is an AC motor and the batteries are DC, an AC to DC inverter is required. The inverter converts stored DC power in the batteries to AC power for use in operating the pumpjack motor. Once again, this conversion is not ideal and the conversion efficiency is only 80%.

Total battery reserve system efficiency is approximately 56% (0.7 x 0.8) from the wind turbine to the pumpjack motor through the battery reserve system. The wind turbine must produce additional power over the year to overcome these inefficiencies and thus maintain the desired power output. On the assumption that the wind generator supplies power directly to the pumpjack motor for 40% of the time and the battery system for 60%, the total power required from the wind generator will be:

$$(0.4 \times 32{,}850) + \frac{(0.6 \times 32{,}850)}{0.56} = 48{,}336 \text{ kwh}$$

This is assuming there are no line losses from the wind generator to the pumpjack motor.

There are also other inefficiencies in the system which include battery power loss due to storage time, reduced battery capacity during cold weather, and power transmission line losses.

Taking into consideration all the above factors, it was determined that a wind turbine generator capable of producing 60,000 kwh per year at the Bone Creek site would supply sufficient power with a reasonable safety margin.

The sixteen wind turbine units identified as possible candidates were once again reviewed and analyzed to determine which unit would provide the necessary power output for the lowest capital cost and still maintain all the necessary operating features.

The unit selected was the Carter Wind Systems Model 25. This machine uses a 440 volt induction generator to produce a maximum of 25 kw at a windspeed of 11.6 m/s. Start-up windspeed is 3.4 m/s and the generator will produce sufficient power to operate the pumpjack motor independently at 6.5 m/s. Complete specifications for the Carter Model 25 are shown in Appendix C, and the power production curve for this unit is shown in Figure 9.

The actual power production of the Carter Model 25 was calculated using Bone Creek wind distribution data and the Model 25 power production curve. The power produced is 60,379 kwh per year; this is detailed in Table 9 and is demonstrated graphically in Figure 10.

Pumpjack motor starting is the remaining consideration. Unfortunately, the induction motor used for pumpjack operation requires a large current draw when starting from a complete stop. Starting currents are usually five times as large as the current draw during full speed operation. This requires the DC to AC inverter to have a sufficient capacity to handle this short (a few seconds) but above average current flow. Continuous power demand is 3.75 kw; the inverter therefore should be rated at approximately 18.75 kw although a 15 kw unit would probably be sufficient.

This system was designed to be completely self-sufficient, supplying all the necessary power to operate the pumpjack 365 days a year. The expected life of the wind turbine generator is 20-25 years; the storage batteries, 15-20 years, and the rectifiers and inverter 20 years.

By designing the two wind power systems, it was observed that wind turbine generators are technically feasible for powering pumpjack motors and that the necessary wind power equipment is commercially available.

IX. WIND SYSTEM ECONOMICS

The economics of the two wind systems were examined and the costs compared to standard oil field operations.

System I

This system used a wind turbine generator to supply electrical power to a lease presently being serviced by a utility network. The power produced by the wind generator is used to reduce the total power consumed from the utility grid. For this system to be ecomomically feasible the wind turbine generator must produce power at a lower cost per kilowatt hour than power from the utility network.

The utility charge for electrical power is a combination of two factors; i) a fixed demand charge based on installed equipment which is paid regardless of whether power is used, and ii) a charge for the actual power consumed. These two costs are added to arrive at the total billing.

The Bone Creek lease has a demand factor of 12 KVA for which it is charged $11.80 per KVA per month. The consumption charge is $0.027 per kwh. The total yearly cost at the Bone Creek lease, assuming a yearly consumption of 32,850 kwh, would be:

$11.80 (12KVA x 12 months) + $0.027 (32,850 kwh) = $2,586.15

This is equivalent to $0.079 per kilowatt hour.

The Tumac Model 680 wind turbine generator selected for this system costs US $13,500 F.O.B. Colorado Springs, Colorado, U.S.A. This price includes rotor assembly, generator, tower pole, and all necessary controls. The estimated delivered price for the Tumac, after paying duty, taxes, exchange and shipping is CDN $21,000. The installation cost was estimated to be $1,000 and it is assumed that the unit will require about $500 per year for maintenance and repairs.

Total yearly power generated by the Tumac unit at the Bone Creek site was calculated to be 16,436 kwh. The cost per generated kilowatt hour for the Tumac unit can be calculated using the formula:

$$\text{cost/kwh} = \frac{(\text{capital cost} \times \text{capital recovery factor}) + \text{annual maintenance cost}}{\text{yearly kilowatt-hours produced}}$$

The capital recovery factor is the per dollar annual cost of the invested capital. To establish the capital recovery factor, the time period over which the investment is to be recovered and the annual interest rate are required. For this analysis we chose 20 years as the recovery period and an annual interest rate of 12%. This yields a capital recovery factor of 0.1339. The cost/kwh can thus be calculated to be:

$$\text{cost/kwh} = \frac{(22{,}000 \times 0.1339) + 500}{16{,}436} = 0.210$$

The cost per generated kwh from the Tumac wind generator is $0.21 and the cost per kwh from the utility network is $.079. The Tumac unit therefore produces power at a cost 2.5 times higher than the power available from the utility network.

System II

This system used a wind turbine generator to supply all power necessary to operate the oil well pumping system. Costs were compared to a propane powered pumpjack installation. The propane system is the most costly system encountered in conventional pumping operations.

To determine costs for a propane powered system, Bone Creek electrical power consumption was "converted" to propane consumption. It was previously determined that the electric pumpjack motor used 3.75 kw of continuous power, which is equivalent to 5.0 horsepower. The assumption was made that the lease would require a 10 hp propane internal combustion engine and operated continuously at 5 hp, and fuel consumption was determined. A conventional oil field propane engine operating at 50% of full load consumes 0.64 lbs. per hp-hour of propane. If the engine was continuously operated at 5 hp for a twenty-four hour period, it would use:

$$\text{Propane used} = \frac{0.64 \text{ lbs}}{\text{hp-hr}} \times 5 \text{ hp} \times \frac{24 \text{ hr}}{\text{day}} = 76.8 \text{ lbs/day}$$

The engine would consume 76.8 lbs of propane per day. There are 0.932 lbs. per litre of propane, therefore, consumption would be 82.4 litres/day. The price for delivered bulk propane averages $0.265/litre. Daily propane costs for operating the pumping system would be:

Daily operating costs = 82.4 ℓ/day x $0.265/ℓ = $21.84/day

Maintenance and repairs for propane systems usually average $400/year or $1.10/day. When maintenance costs were added to the daily operating cost, the total daily cost was determined for the propane system:

Total daily cost = $21.84 + $1.10 = $22.94

A list of the capital equipment necessary to construct the wind powered system follows:

	Cost
Cart Wind Systems, Model 25	$
Wind Turbine Generator	
(delivered, tax and duty paid)	40,000
15 KVA DC to AC 3-phase inverter system	22,500
Control panel with 3-phase rectifier	
fuses, instruments, voltage limiter	5,500
Stationary lead-acid batteries	
600 kwh capacity	35,000
System wiring and installation	2,000
Total System Cost	$105,000

Yearly maintenance costs are expected to be approximately $1,000 which includes both wind turbine and battery storage system upkeep.

Total power generated by the Carter Model 25 over a year is 60,379 kwh but only 32,850 kwh is actually consumed by the pumpjack motor. The difference between wind generator output and final consumption is a consequence of system inefficiencies, mostly occurring in the battery storage system.

The cost per kilowatt hour of this wind powered system is calculated using the formula:

$$\text{Cost/kwh} = \frac{(\text{capital cost} \times \text{capital recovery factor}) + \text{annual maintenance cost}}{\text{yearly kilowatt-hours}}$$

Here, once again the capital recovery factor of 0.1339 will be used, (20 year term at 12% per annum):

$$\text{Cost/kwh} = \frac{(105{,}000 \times 0.1339)}{32{,}850} + 1000 = \$0.458/\text{kwh}$$

The pumpjack motor draws a constant 3.75 kw which results in daily consumption of (3.75kw x 24 hours) = 90 kwh. The total daily operating costs of the wind system are calculated below:

Total Daily Operating Costs = 90 kwh x \$0.458/kwh = \$41.22

The daily operating costs of System II would be approximately 80% higher than the operating costs of the propane powered system.

X. DISCUSSION AND CONCLUSIONS

The use of wind turbine generating systems to supply electrical power for oil well pumpjack operation is not presently feasible.

Technically, a wind turbine generating system can be designed to supply the necessary power for pumpjack operation. Unfortunately, the reliability of such systems in the oil field is unknown. It is anticipated that operational problems with System II would arise because of its unique application. Since no commercial electric wind powered oil well pumping systems are available, one cannot refer to documented experience to aid in the design or operation of a successful installation.

Economically it was shown that both of the two wind turbine generating systems studied delivered power at a price substantially higher than that of the utility electricity or propane they augmented or supplanted. The operating costs for the two systems are summarized below:

System I	(Electrified Lease)	
	utility grid power	$0.079/kwh
	wind generated power	$0.210/kwh

System II (remote location)

Propane powered	$22.94/day
Wind powered	$41.22/day

It should be noted that these figures were calculated using the location with the best wind profile. Other locations with poorer wind profiles, which includes the majority of Saskatchewan, would have higher operating costs and reduced overall performance.

Of the two systems studied, System II (the remote location case) comes closer to being economically viable. Unfortunately there are very few 100% propane oil well pumping installations as assumed by System II. Whenever possible casing gas (natural gas) from the wellhead is used to power the pumpjack engine; if casing gas supply is insufficient, propane is used to supplement the gas supply. Using casing gas greatly reduces operating costs which would result in a greater operating cost differential between the wind powered system and casing gas-propane systems. Even if the wind powered operation described by System II could be made economically feasible it would have limited applicability to systems presently operating with 100% propane.

The two wind power systems studied in this report indicate that when the increased operating costs, unknown reliability, operational problems, and limited applicability of wind power systems are considered, wind powered oil well pumping is not presently feasible.

XI. RECOMMENDATIONS

Although the use of wind turbine generators for oil field pumping is currently unjustified, such factors as rapidly increasing utility rates, wind power tax credits and government funded incentives or cheaper energy storage devices could result in wind powered pumping systems becoming economically feasible in the future. It is therefore recommended that changes in wind energy policy, utility pricing, and new technical developments be monitored, and when conditions warrant further analysis, a reassessment of wind powered oil well pumping be carried out.

TABLE 1 - CLIMATRONICS WEATHER STATION--SPECIFICATIONS

Sensor Specifications (Meets PSD Guidelines for Meteorological Instrumentation)					
	Accuracy	**Range***	**Distance or Time Constant**	**Threshold**	**Damping Ratio**
Wind Speed	±0.25 mph or 1.5% ±0.12 m/s	0-140 mph 0-65 m/s	8 Ft. Max. 2.5 m Max.	0.75 mph 0.34 m/s	
Wind Direction	±1.5°	0-360° Mech. 0-540° Elect.	8 Ft. Max. 2.5 m Max.	0.75 mph 0.34 m/s	0.4-0.6
Relative Humidity	±4% 0-100% R.H.	0-100% R.H.	10 Sec.		
Temperature (Air, Water, Soil)	±1.0°F ±0.5°C	-40 to 120°F -30 to 50°C	10 Sec.		
Solar Radiation	±5%	0 to infinity			
Rain/Snow	±1%	0 to infinity			
Dew Point	±1.0°F ±0.5°C	-40 to + 110°F 40 to 42°C	1°/Min.		
Barometric Pressure	±0.4" ±1 mb	any 4" interval any 100 mb interval	10 Sec.		

*Other Ranges Available (Consult Factory)

Dimensions				
	Height	**Width**	**Length**	**Weight**
Recorder	10.5" 26.7 cm	9.75" 24.8 cm	13.5" 34.3 cm	28 lbs. 12.7 KG
Carrying Case	15.5" 39.4 cm	5.75" 14.6 cm	30.75" 78.1 cm	15 lbs. 6.8 KG
Crossarm Assembly	8" 20.3 cm	3" 7.6 cm	28" 71.1 cm	3 lbs. 1.36 KG
Tripod	4-10' 1.2-3 m	40" 1 m	40" 1 m	25 lbs. 11.34 KG

Carrying Case

A fiberglass carrying case is included with the EWS. This carrying case has a foam rubber insert which insures protection of the sensors during transit.

Accessories

The EWS comes complete and ready to operate. All sensors mount on ¾ pipe (1.05" O.D.). The only possible accessories necessary are the 10' expandable tripod or C-33 10 meter tower.

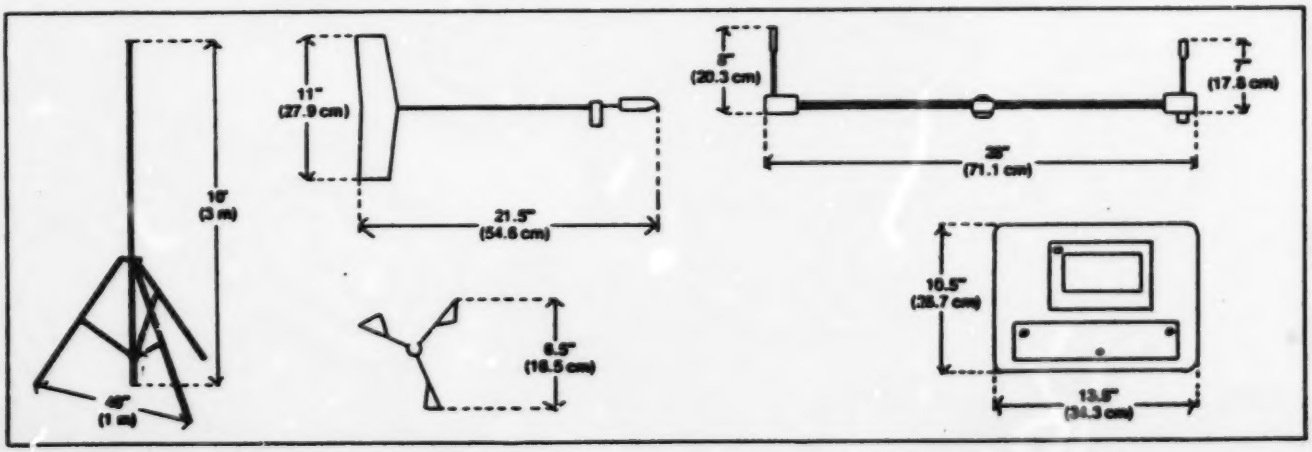

TABLE 2 - SAMPLE OF A WIND DATA DAILY RECORD SHEET

BONE CREEK (14-27-10-19-W3)

DATE: Jan 16/82

TIME:	WIND SPEED(km/hr) (Avg)	Instant	TEMPERATURE(C)	WIND DIRECTION
1	36.0	37.8	-29.1	
2	36.0	32.4	-29.0	
3	16.2	14.4	-29.9	
4	10.8	10.8	-29.9	
5	10.8	10.8	-29.5	
6	18.0	27.0	-26.0	
7	21.0	16.2	-26.0	
8	7.2	7.2	-25.0	
9	7.2	7.2	-27.0	
10	9.0	9.0	-27.0	
11	10.8	10.8	-26.0	
12	10.8	10.8	-22.0	wind out
13	10.8	10.8	-18.9	
14	14.4	14.4	-19.0	
15	19.8	18.0	-19.0	
16	17.6	14.8	-19.0	
17	19.8	19.8	-19.8	
18	25.2	25.2	-20.0	
19	32.4	34.2	-20.0	
20	32.4	32.4	-19.5	
21	30.0	27.0	-18.6	
22	28.8	27.0	-18.0	
23	30.6	27.0	-19.0	
24	23.4	25.2	-14.0	

PEAK GUST(km/hr) 27.0/14[40]

39.6/22[15]

TABLE 3 - BONE CREEK WINDSPEED DISTRIBUTION

WINDSPEED m/s	FREQUENCY	CUMMULATIVE FREQUENCY	PERCENT	CUMMULATIVE PERCENT
0	29	29	0.185	0.185
1	797	826	5.072	5.256
2	1736	2562	11.047	16.303
3	1963	4525	12.491	28.794
4	1888	6413	12.014	40.808
5	1650	8063	10.500	51.308
6	1414	9477	8.998	60.305
7	1257	19734	7.999	68.304
8	1194	11928	7.598	75.902
9	915	12843	5.822	81.724
10	837	13680	5.326	87.051
11	461	14141	2.934	89.984
12	427	14568	2.717	92.701
13	264	14832	1.680	94.381
14	228	15060	1.451	95.832
15	225	15285	1.432	97.264
16	94	15379	0.598	97.862
17	79	15458	0.503	98.365
18	81	15539	0.515	98.880
19	51	15590	0.325	99.205
20	57	15647	0.363	99.567
21	22	15669	0.140	99.707
22	17	15686	0.108	99.815
23	21	15707	0.134	99.949
24	6	15713	0.038	99.987
25	1	15714	0.006	99.994
27	1	15715	0.006	100.000

TABLE 4 - RAPDAN WINDSPEED DISTRIBUTION

WINDSPEED m/s	FREQUENCY	CUMMULATIVE FREQUENCY	PERCENT	CUMMULATIVE PERCENT
0	155	155	3.062	3.062
1	785	940	15.508	18.570
2	877	1817	17.325	35.895
3	802	2619	15.844	51.738
4	621	3240	12.268	64.006
5	605	3845	11.952	75.958
6	415	4260	8.198	84.156
7	284	4544	5.610	89.767
8	213	4757	4.208	93.975
9	117	4874	2.311	96.286
10	101	4975	1.995	98.281
11	39	5014	0.770	99.052
12	14	5028	0.277	99.328
13	11	5039	0.217	99.546
14	21	5060	0.415	99.960
15	2	5062	0.040	100.000

TABLE 5 - WEYBURN WINDSPEED DISTRIBUTION

WINDSPEED m/s	FREQUENCY	CUMMULATIVE FREQUENCY	PERCENT	CUMMULATIVE PERCENT
0	46	46	1.296	1.296
1	375	421	10.563	11.859
2	579	1000	16.310	28.169
3	679	1679	19.127	47.296
4	537	2216	15.127	62.423
5	388	2608	10.930	73.352
6	284	2888	8.000	81.352
7	231	3119	6.507	87.859
8	159	3278	4.479	92.338
9	90	3368	2.535	94.873
10	77	3445	2.169	97.042
11	51	3496	1.437	98.479
12	37	3533	1.042	99.521
13	8	3541	0.225	99.746
14	7	3548	0.197	99.944
15	2	3550	0.056	100.000

TABLE 6 - BONE CREEK WIND DIRECTION DISTRIBUTION

COMPASS DIRECTION	FREQUENCY	CUMULATIVE FREQUENCY	PERCENT	CUMULATIVE PERCENT
North	356	356	6.601	6.601
N.E.	288	644	5.340	11.941
East	472	1116	8.752	20.693
S.E.	431	1547	7.992	28.685
South	1103	2650	20.452	49.138
S.W.	596	3246	11.051	60.189
West	1029	4275	19.080	79.269
N.W.	1118	5393	20.731	100.000

STATISTICAL ANALYSIS SYSTEM 13:51 TUESDAY, AUGUST 2, 1983 1

TABLE OF SPEED BY COMPASS

SPEED COMPASS

SPEED	FREQUENCY / PERCENT / ROW PCT / COL PCT	.	North	NE	East	SE	South	SW	West	NW	TOTAL
.		510	0	0	0	0	0	0	0	0	.
		.	.	.	.	.	.	.	.	.	.
		.	.	.	.	.	.	.	.	.	
		.	.	.	.	.	.	.	.	.	
< 11 km/h		2511	75	133	106	192	358	139	187	123	1269
		.	1.39	2.47	1.97	3.56	6.56	2.58	2.73	2.28	23.53
		.	5.91	10.48	8.35	15.13	27.90	10.95	11.58	9.69	
		.	21.07	46.18	22.46	44.55	32.09	23.32	18.29	11.00	
11-16 km/h		1261	59	84	71	53	219	127	158	151	922
		.	1.09	1.56	1.32	0.98	4.06	2.35	2.93	2.80	17.10
		.	6.40	9.11	7.70	5.75	23.75	13.77	17.18	16.38	
		.	16.57	29.17	15.04	12.30	19.89	21.31	15.35	13.51	
16-21 km/h		1179	88	41	86	67	191	110	178	155	912
		.	1.63	0.76	1.59	1.24	3.54	2.04	3.23	2.87	16.91
		.	9.65	4.50	9.43	7.35	20.94	12.06	19.08	17.00	
		.	24.72	14.24	18.22	15.55	17.32	18.46	16.91	13.86	
21-26 km/h		1480	69	29	129	54	181	112	184	157	915
		.	1.28	0.54	2.39	1.00	3.36	2.08	3.41	2.91	16.97
		.	7.54	3.17	14.10	5.90	19.78	12.24	20.11	17.16	
		.	19.38	10.07	27.33	12.53	16.41	18.79	17.88	14.04	
26-31 km/h		964	24	0	47	25	73	90	120	108	887
		.	0.45	0.00	0.87	0.46	1.35	0.93	2.23	2.00	8.29
		.	5.37	0.00	10.51	5.59	16.33	11.19	26.85	24.16	
		.	6.74	0.00	9.96	5.80	6.62	8.39	11.66	9.86	
31-36 km/h		1142	29	1	22	24	67	45	151	185	524
		.	0.54	0.02	0.41	0.45	1.24	0.83	2.80	3.43	9.72
		.	5.53	0.19	4.20	4.58	12.79	8.59	28.82	35.31	
		.	8.15	0.35	4.66	5.57	6.07	7.55	14.67	16.55	
36-41 km/h		336	4	0	4	7	10	8	59	69	157
		.	0.07	0.00	0.07	0.13	0.19	0.07	1.09	1.28	2.91
		.	2.55	0.00	2.55	4.46	6.37	2.55	37.58	43.95	
		.	1.12	0.00	0.85	1.62	0.91	0.67	5.73	6.17	
41-46 km/h		410	4	0	3	3	7	9	26	81	133
		.	0.07	0.00	0.06	0.06	0.13	0.17	0.48	1.50	2.47
		.	3.01	0.00	2.26	2.26	5.26	6.77	19.55	60.90	
		.	1.12	0.00	0.64	0.70	0.63	1.51	2.53	7.25	
TOTAL		.	356	288	472	431	1103	596	1029	1118	5393
		.	6.60	5.34	8.75	7.99	20.45	11.05	19.08	20.71	100.00

(CONTINUED)

STATISTICAL ANALYSIS SYSTEM 13:51 TUESDAY, AUGUST 2, 1983 8

TABLE OF SPEED BY COMPASS

SPEED COMPASS

FREQUENCY / PERCENT / ROW PCT / COL PCT	.	North	NE	East	SE	South	SW	West	NW	TOTAL
46-51 km/h	370	4	0	4	6	1	0	1	68	84
	.	0.07	0.00	0.07	0.11	0.02	0.00	0.02	1.26	1.56
	.	4.76	0.00	4.76	7.14	1.19	0.00	1.19	80.95	
	.	1.12	0.00	0.85	1.39	0.09	0.00	0.10	6.08	
51-56 km/h	228	0	0	0	0	0	0	9	18	27
	.	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.33	0.50
	.	0.00	0.00	0.00	0.00	0.00	0.00	33.33	66.67	
	.	0.00	0.00	0.00	0.00	0.00	0.00	0.87	1.61	
56-61 km/h	106	0	0	0	0	0	0	0	2	2
	.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.04
	.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	
	.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.18	
61-66 km/h	152	0	0	0	0	0	0	0	1	1
	.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02
	.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	
	.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	
66-71 km/h	76	0	0	0	0	0	0	0	0	0
	.	.	.	.	.	.	.	.	.	0.00
	.	.	.	.	.	.	.	.	.	
	.	.	.	.	.	.	.	.	.	
76-81 km/h	22	0	0	0	0	0	0	0	0	0
	.	.	.	.	.	.	.	.	.	0.00
	.	.	.	.	.	.	.	.	.	
	.	.	.	.	.	.	.	.	.	
81-86 km/h	21	0	0	0	0	0	0	0	0	0
	.	.	.	.	.	.	.	.	.	0.00
	.	.	.	.	.	.	.	.	.	
	.	.	.	.	.	.	.	.	.	
86-91 km/h	7	0	0	0	0	0	0	0	0	0
	.	.	.	.	.	.	.	.	.	0.00
	.	.	.	.	.	.	.	.	.	
	.	.	.	.	.	.	.	.	.	
OVER 91 km/h	1	0	0	0	0	0	0	0	0	0
	.	.	.	.	.	.	.	.	.	0.00
	.	.	.	.	.	.	.	.	.	
	.	.	.	.	.	.	.	.	.	
TOTAL	.	356	288	472	431	1103	596	1029	1116	5391
	.	6.60	5.34	8.75	7.99	20.45	11.05	19.08	20.73	100.00

TABLE 8 - SYSTEM I POWER DISTRIBUTION

WINDSPEED m/s	HOURS PER YEAR (hr)	TUMAC POWER @ WINDSPEED (kw)	YEARLY POWER PRODUCED (kwh)
0	16.2	0	0
1	444.3	0	0
2	967.7	0	0
3	1094.2	0	0
4	1052.4	0	0
5	919.8	0.15	138
6	788.2	0.80	631
7	700.7	1.6	1,120
8	665.6	2.6	1,730
9	510.0	3.7	1,887
10	466.6	5.0	2,333
11	257.0	6.3	1,619
12	238.0	7.2	1,713
13	147.2	8.2	1,207
14	127.1	8.8	1,118
15	125.4	9.0	1,128
16	52.4	9.2	482
17	44.1	9.0	397
18	45.1	8.7	393
19	28.5	8.1	231
20	31.7	7.2	229
21	12.3	6.5	80
22	9.5	0	0
23	11.7	0	0
24	3.3	0	0
25	0.5	0	0
26	0	0	0

TABLE 9 SYSTEM II POWER DISTRIBUTION

WINDSPEED m/s	HOURS PER YEAR (hr)	TURBINE POWER @ WINDSPEED (kw)	YEARLY POWER PRODUCED (kwh)
0	16.2	0	0
1	444.3	0	0
2	967.7	0	0
3	1094.2	0	0
4	1052.4	0.4	421
5	919.8	1.5	1,380
6	788.2	2.0	1,576
7	700.7	5.5	3,854
8	665.6	9.2	6,124
9	510.0	13.5	6,885
10	466.6	19.0	8,865
11	257.0	23.5	6,040
12	238.0	26.8	6,378
13	147.2	28.4	4,180
14	127.1	29.4	3,736
15	125.4	29.9	3,749
16	52.4	30.0	1,572
17	44.1	30.0	1,323
18	45.1	30.0	1,353
19	28.5	30.0	855
20	31.7	30.0	954
21	12.3	30.0	369
22	9.5	30.0	285
23	11.7	30.0	351
24	3.3	30.0	99
25	0.5	30.0	15
26	0	30.0	0
27	0.5	30.0	15
		TOTAL	60,379

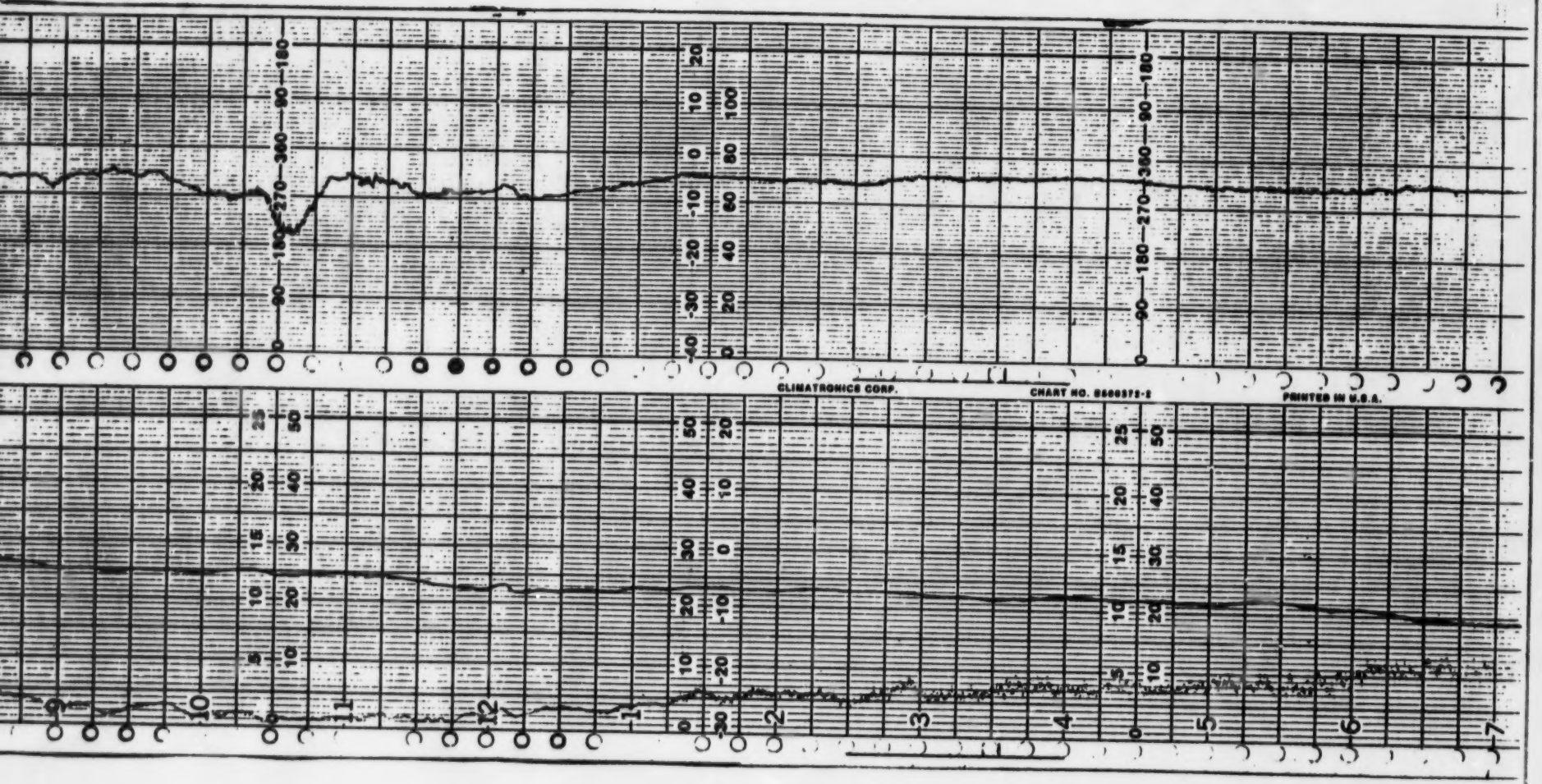

FIGURE 1. WEATHER STATION STRIPCHART SAMPLE

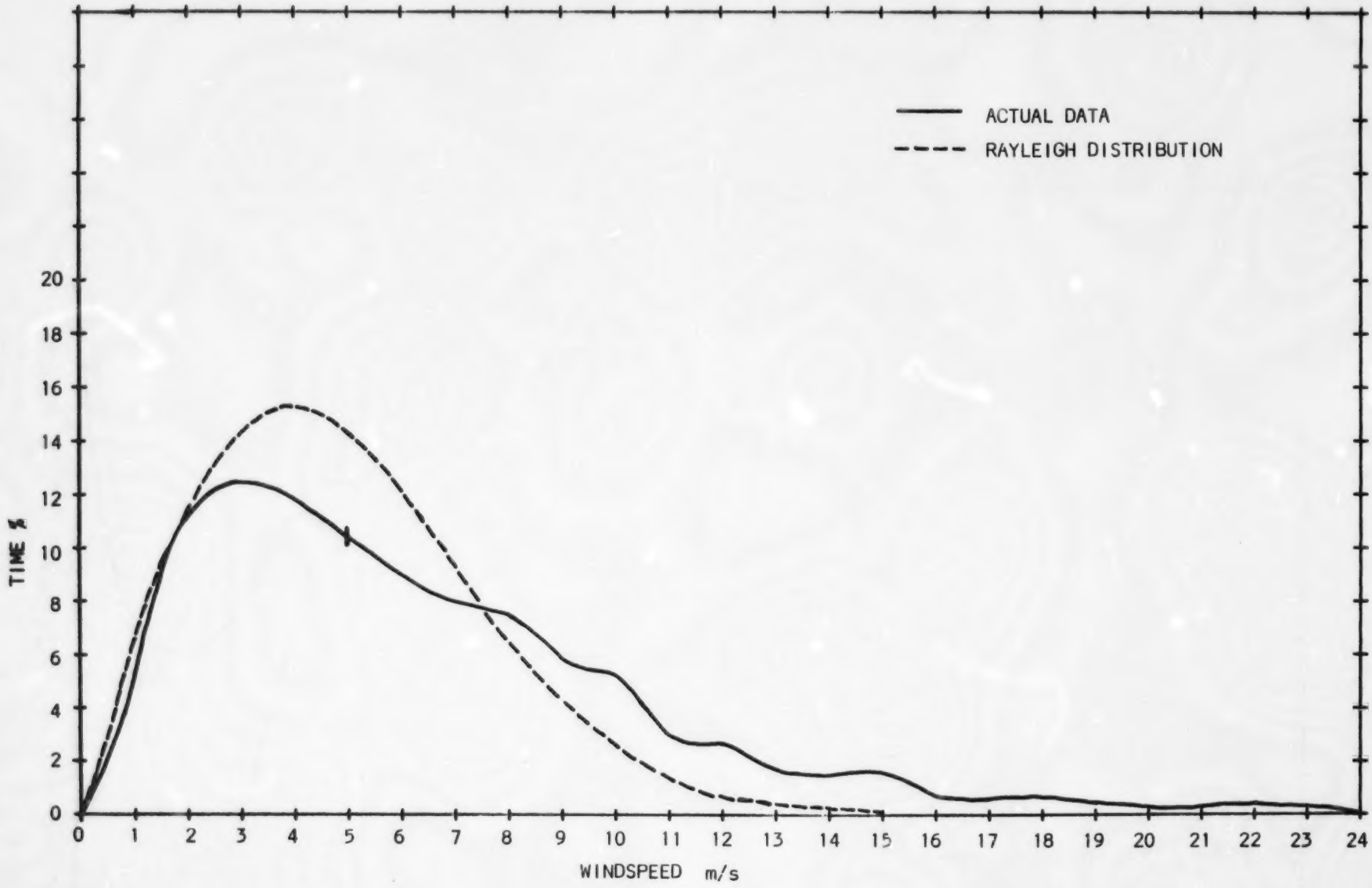

FIGURE 2. BONE CREEK 14-27-10-19 W3M WINDSPEED DISTRIBUTION

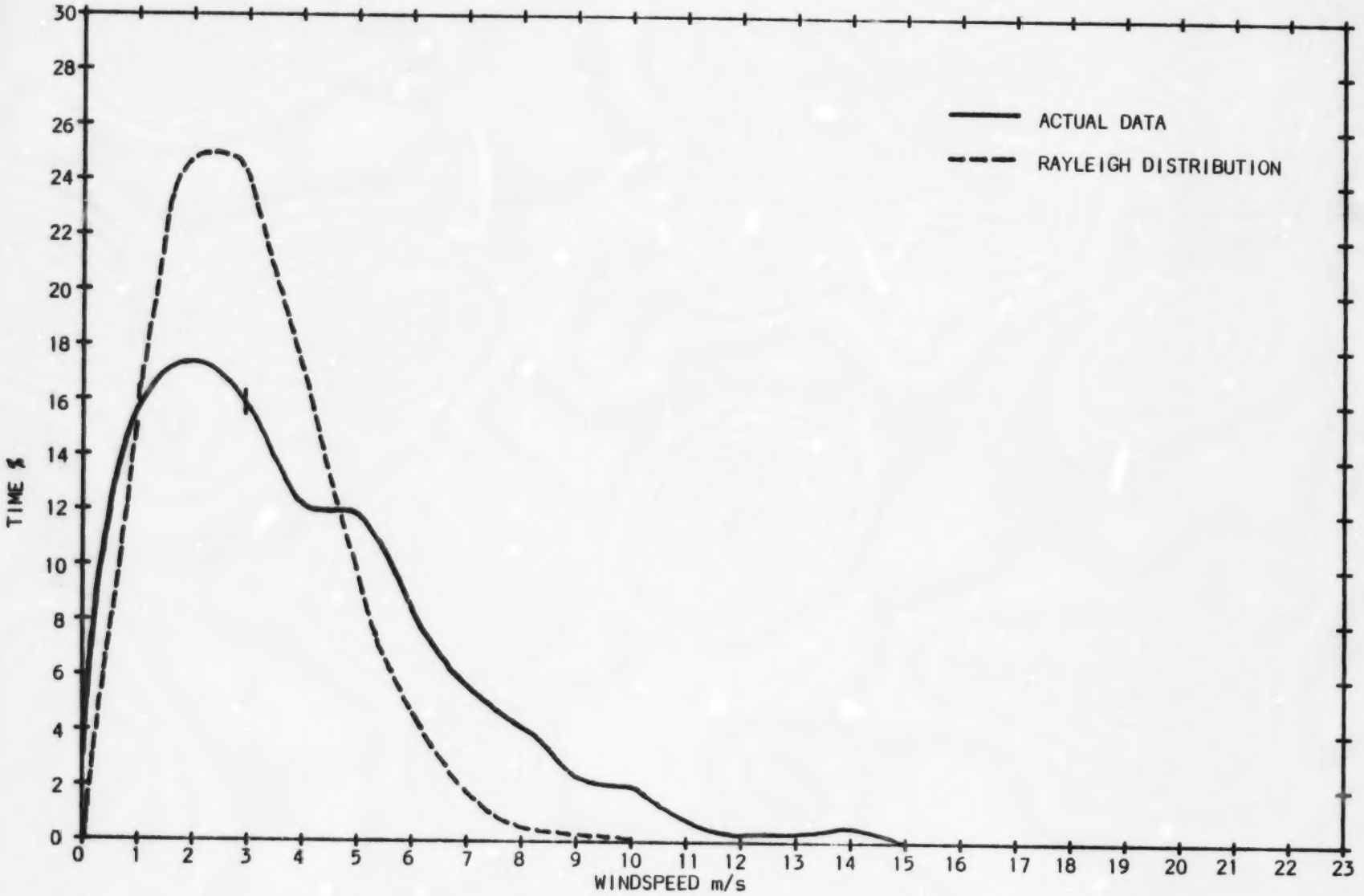

FIGURE 3. RAPDAN 16-5-4-20 W3M WINDSPEED DISTRIBUTION

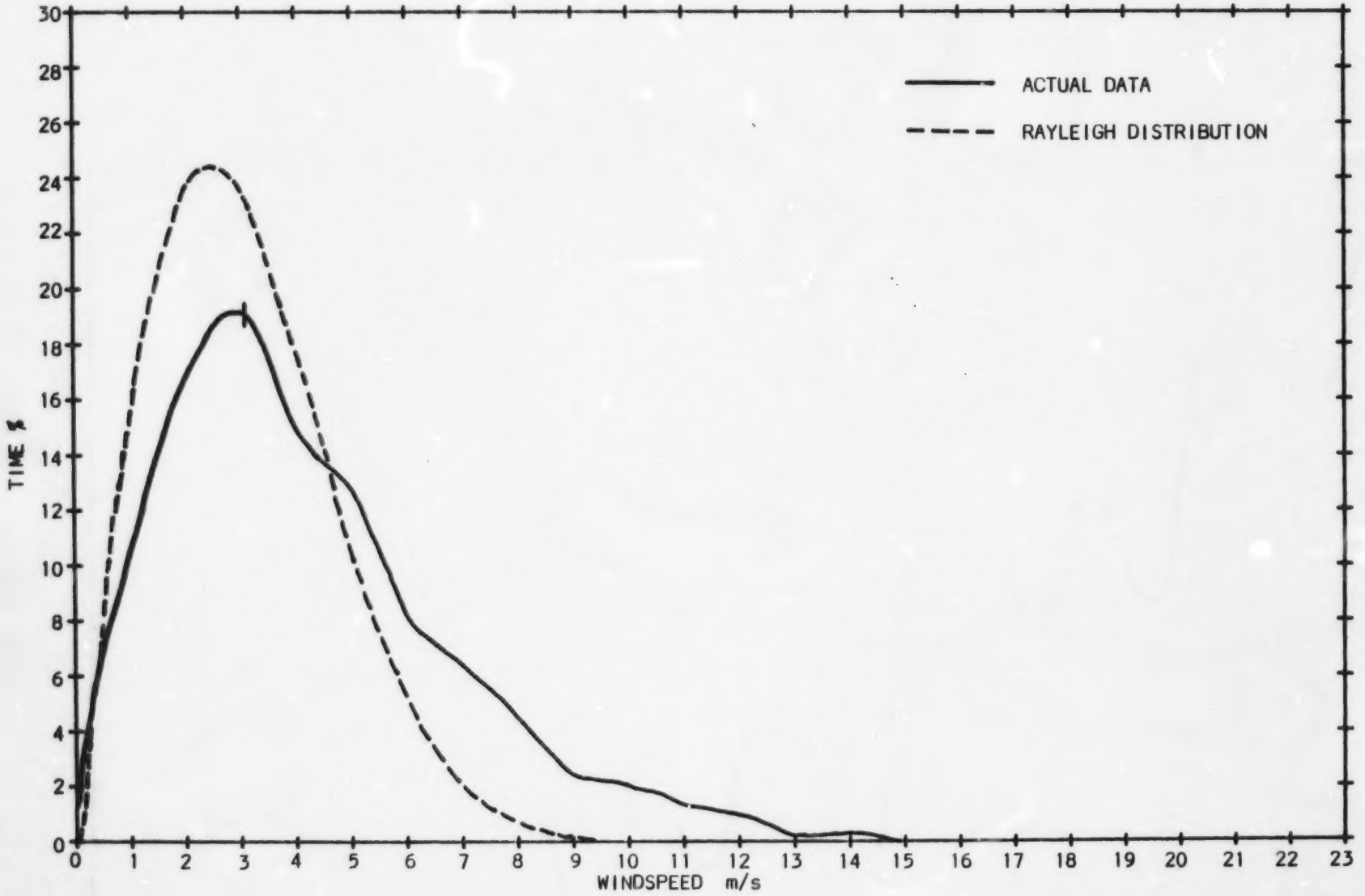

FIGURE 4. WEYBURN 10-2-7-13 W2M WINDSPEED DISTRIBUTION

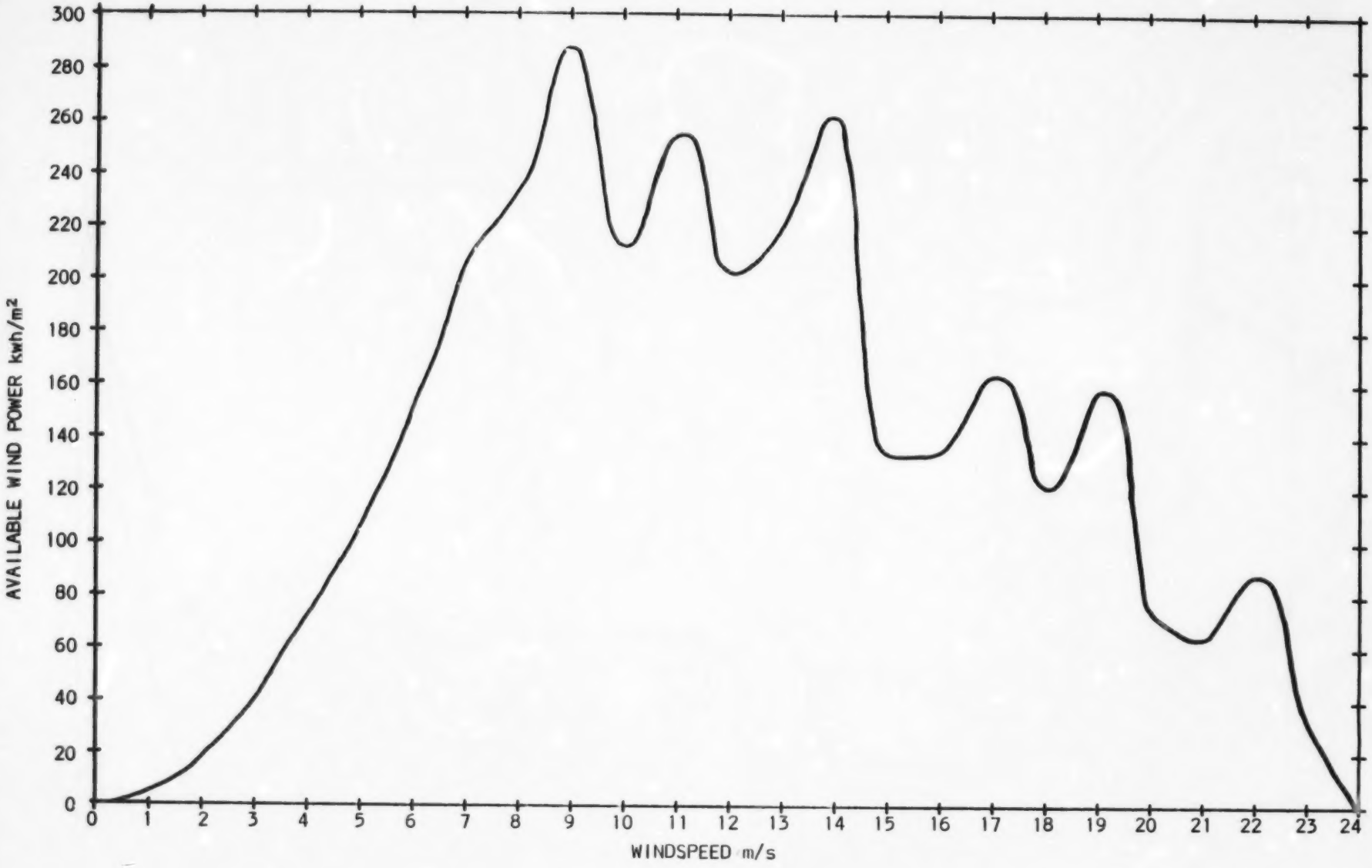

FIGURE 5. BONE CREEK 14-27-10-19 W3M WIND POWER DISTRIBUTION

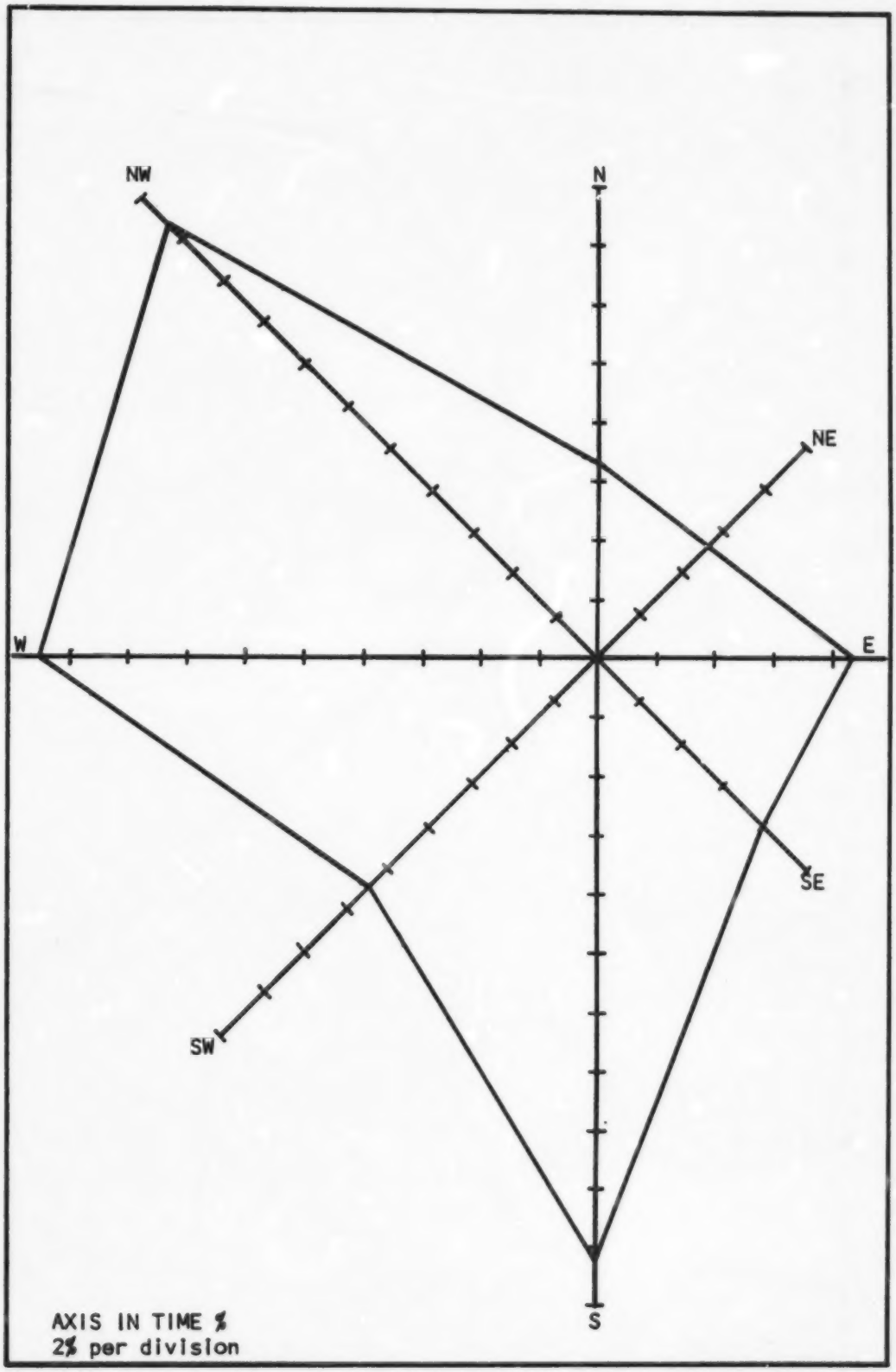

FIGURE 6. BONE CREEK ROSE.

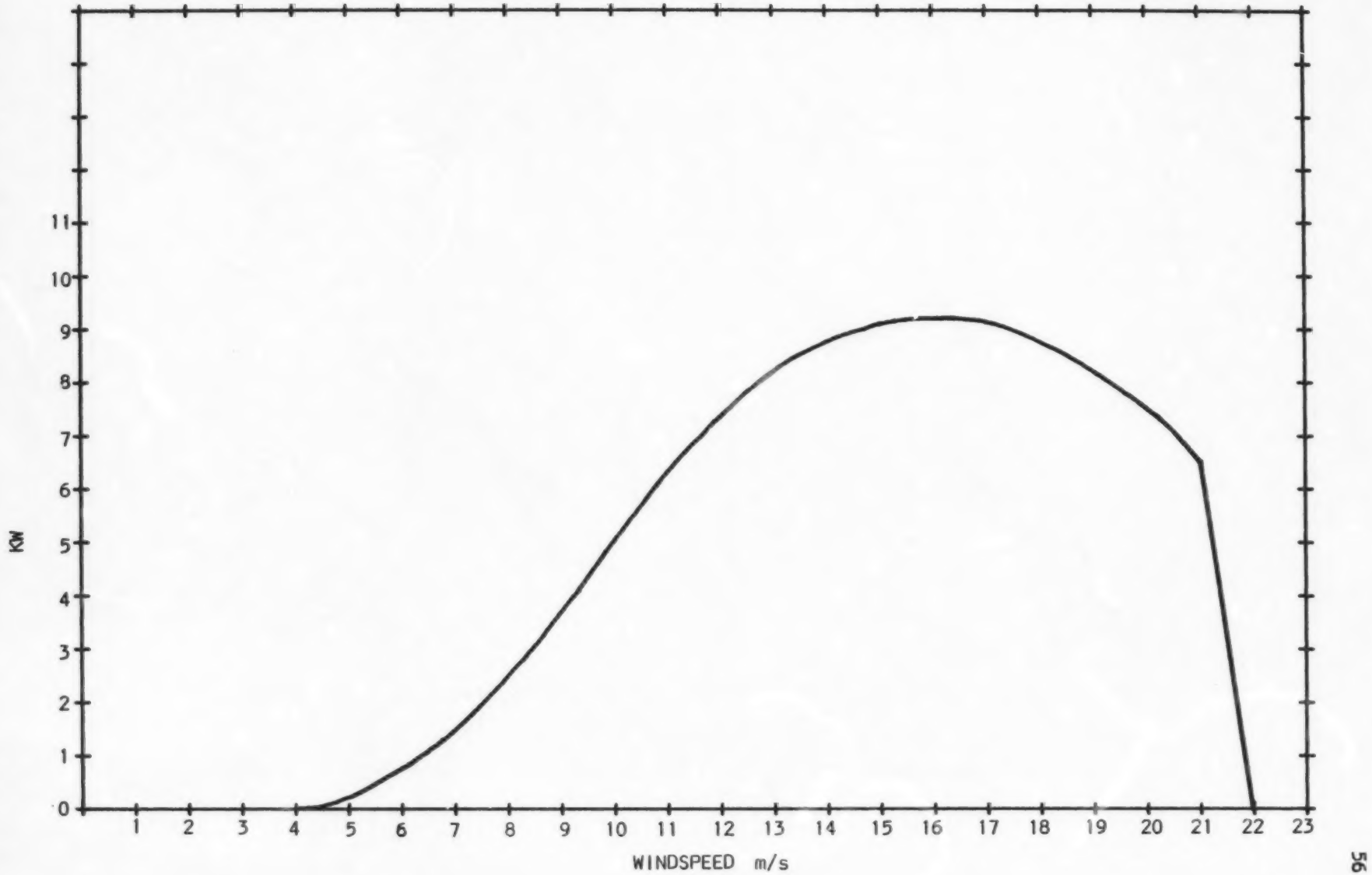

FIGURE 7. TUMAC MODEL 680. POWER OUTPUT VS WINDSPEED.

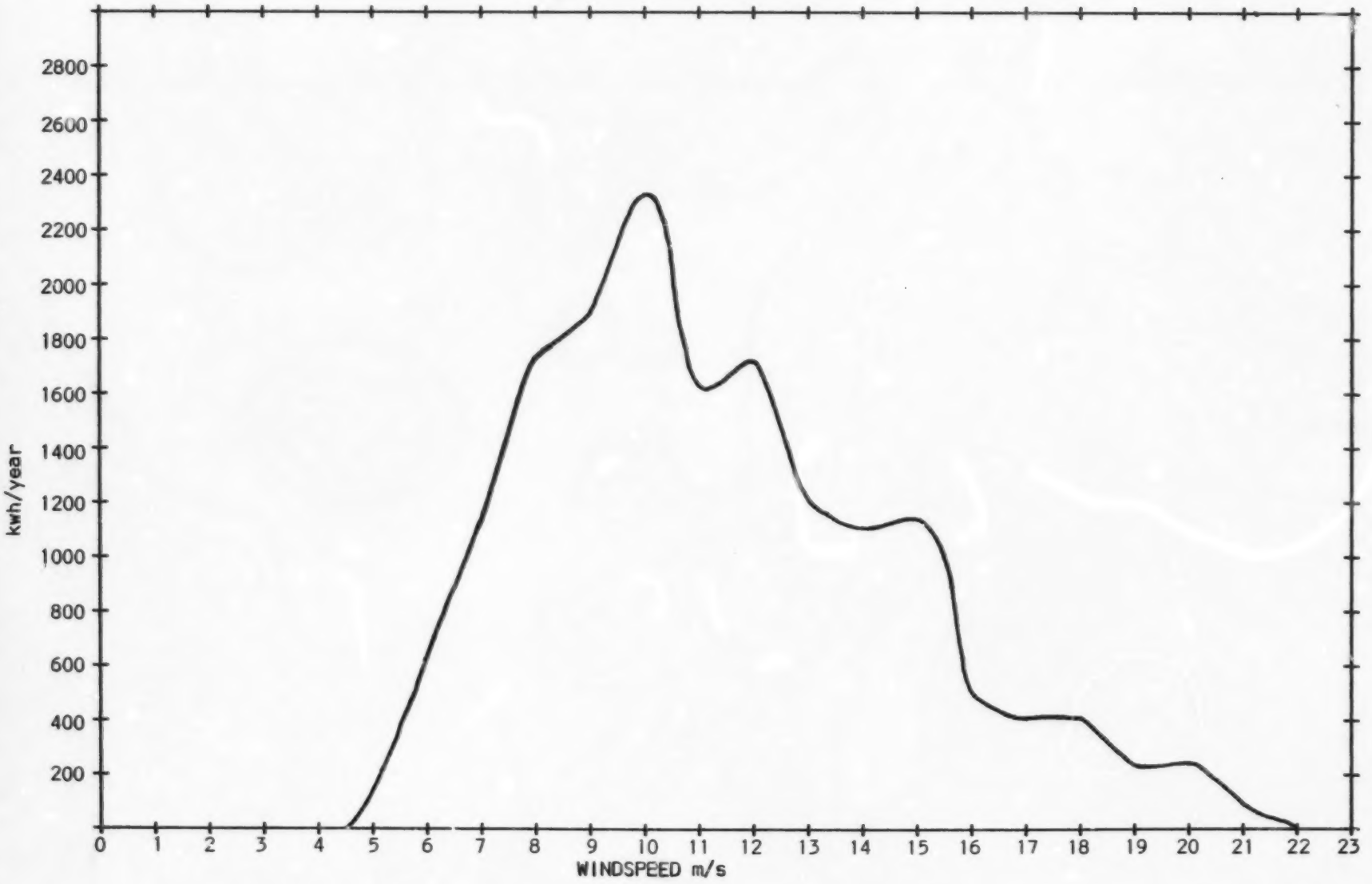

FIGURE 8. SYSTEM I - POWER DISTRIBUTION.

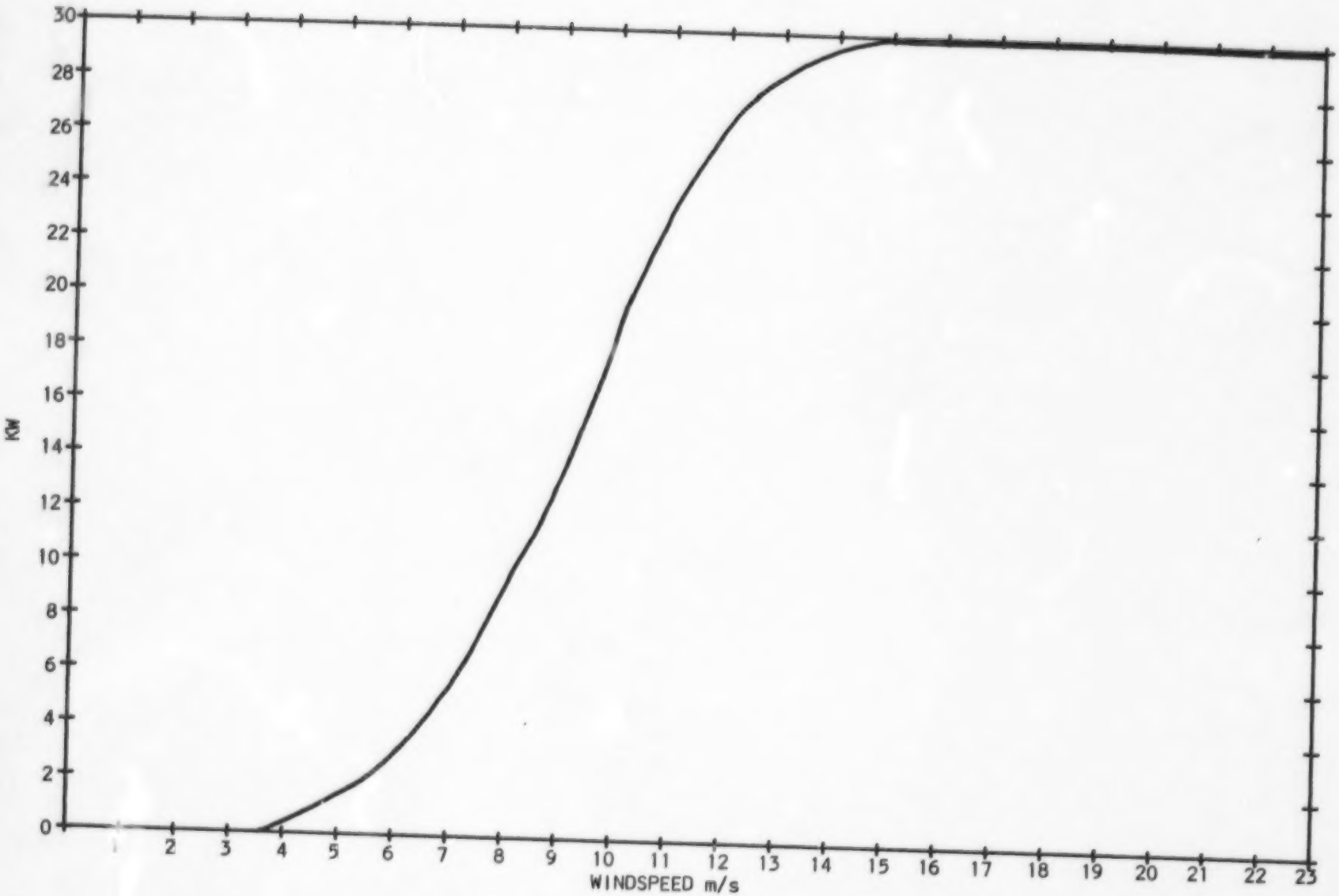

FIGURE 9. CARTER WIND SYSTEMS MODEL 25. POWER OUTPUT VS WINDSPEED.

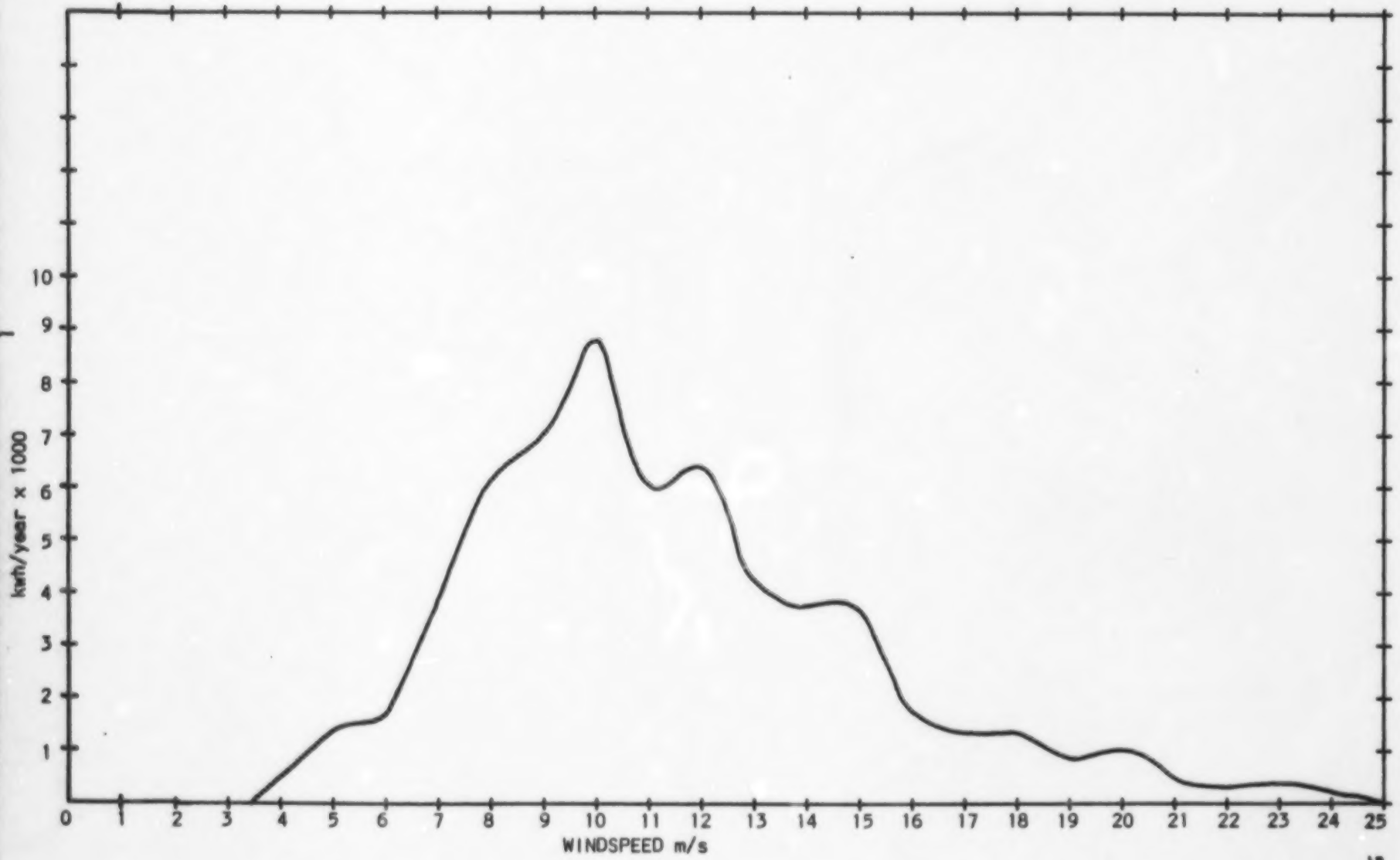

FIGURE 10. SYSTEM II - POWER DISTRIBUTION.

APPENDIX A

Site Selection Criteria

APPENDIX A

SITE SELECTION CRITERIA

Differential heating of the atmosphere gives rise to the existence of pressure gradients, the driving force for the wind. As the synoptic scale pressure patterns (scale 1000 to 1500 km) migrate from west to east the local topography, local heating/cooling conditions and surface roughness exert influence on the wind system. Rough surfaces such as trees or buildings create friction which reduces wind speeds near the surface. Turbulence at a particular site is influenced by local roughness and topography. Zones of high turbulence can lead to damage of the wind equipment and reduction in the production of power. Areas of high wind shear should also be avoided as wind power sites: for this purpose zones of high wind shear can be considered to be areas in which large changes in wind speed or direction occur in distances less than or equal to the diameter of the wind machine rotor.

Clearly, where they can be identified, areas with a high frequency of electrical storms or icing conditions should also be avoided.

For siting of wind systems, terrain may be considered flat if it meets three criteria:

1. if the elevation difference between the site and the surrounding terrain is less than 60 m in 5 km;

2. if the ratio of the height from the bottom of the rotor to the bottom of the tower to the distance from the foot to the crest of the nearest local relief is less than 0.02;
3. if the entire wind machine rotor is at a height equal to or greater than three times the greatest difference in terrain elevation for 4 km in any direction.

Under flat terrain conditions, only changes in roughness and tower height affect the wind regime for power development.

In the case of non-flat terrain, several siting categories exist:

1. hills,
2. ridges,
3. cliffs,
4. valleys.

Generally, in non-flat terrain the influence of the topographic features exceeds that of roughness or artificial barriers.

For the present purposes, ridges can be defined as elongated hills, rising from 500 to 2,000 feet and having little or no flat area at the summit. The maximum acceleration at a ridge summit occurs when the prevailing wind blows perpendicular to the ridge line. When the wind is perpendicular to the ridge line, the

ridge on the windward side may further funnel the wind, increasing acceleration. Note that the lee of the ridge line is the zone of maximum turbulence. In classifying ridges note:

Suitability	Slope Angle
Ideal	16°
Very Good	10°
Fair	3°
Avoid	less than 3°
	more than 27°

Hills are considered to be 500 feet to 2,000 feet high, detached from ridges and with a length less than 10 times its height. Hills do not produce as much acceleration as ridges, as air flow around them reduces the potential acceleration. The best sites along isolated hills are tangential to the prevailing wind direction. Siting on isolated hills should be ranked as follows:

Suitability	Location
Best	Upper half of hills tangent to prevailing winds
Good	Top of hills
Fair	Upper half of windward hill face
Avoid	Foot of hill, leeward half of hill

Valleys, in some locations, are prone to katabatic drainage winds and may constitute a smooth, low-level path for air circulation. Where channels are deep, they may be prone to turbulence and shear. The valley funnelling effect (except in mountainous areas) can only be used effectively where the valley lines up with the prevailing wind.